A Deep Ocean Anti-Neutrino Observatory

An Introduction to the Science Potential of

Hanohano

A First Step for Long Range Anti-Neutrino Monitoring
Of Reactors and Weapons from the Deep Ocean

Presented by
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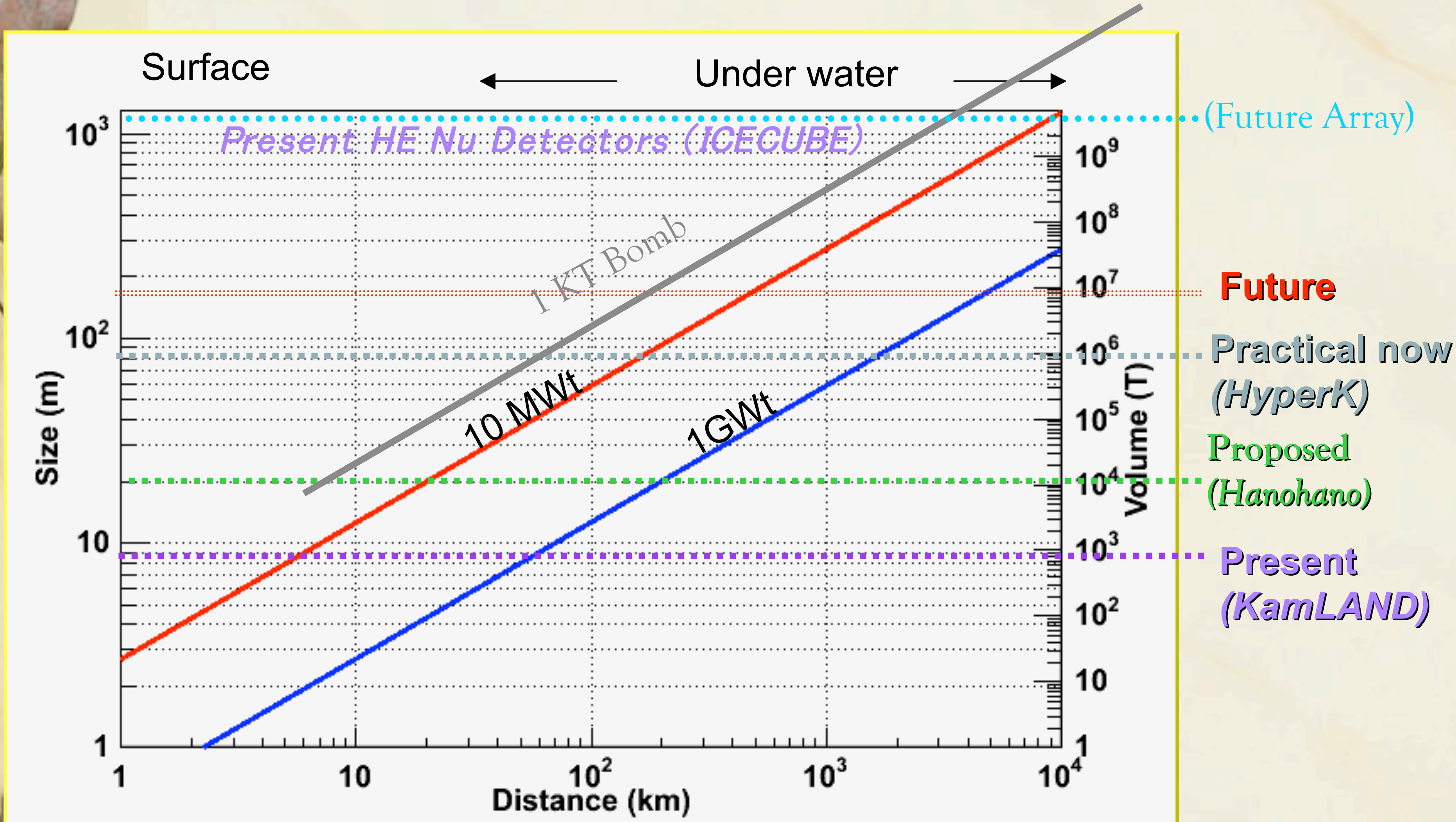
Hanohano Origins

- Started as an exercise in ’03 investigating future potential for world reactor and weapons testing monitoring (see Guillian report), inspired by DTRA inquiry.
- Workshop in 1/04 concluded that such will be possible, with giant detectors, and technology just being developed.
  - http://www.phys.hawaii.edu/~jgl/nacw.html
- Plan is to get experience with remote monitoring with a detector that can be built today.
- Have identified at geology & physics workshops in ’05 UH and ’06 AGU Baltimore, NOW06 Italy, NNN06 Seattle, great science which a 10 kiloton deep ocean, portable, detector can accomplish.
  - UH 12/05 http://www.phys.hawaii.edu/~sdye/hnsc.html
  - AGU 5/06 http://www.agu.org/meetings/sm06/sm06sessions/sm06_U41F.html
  - Italy 9/06 http://www.ba.infn.it/~now2006/
  - Seattle 9/06 http://neutrino.phys.washington.edu/nnn06/

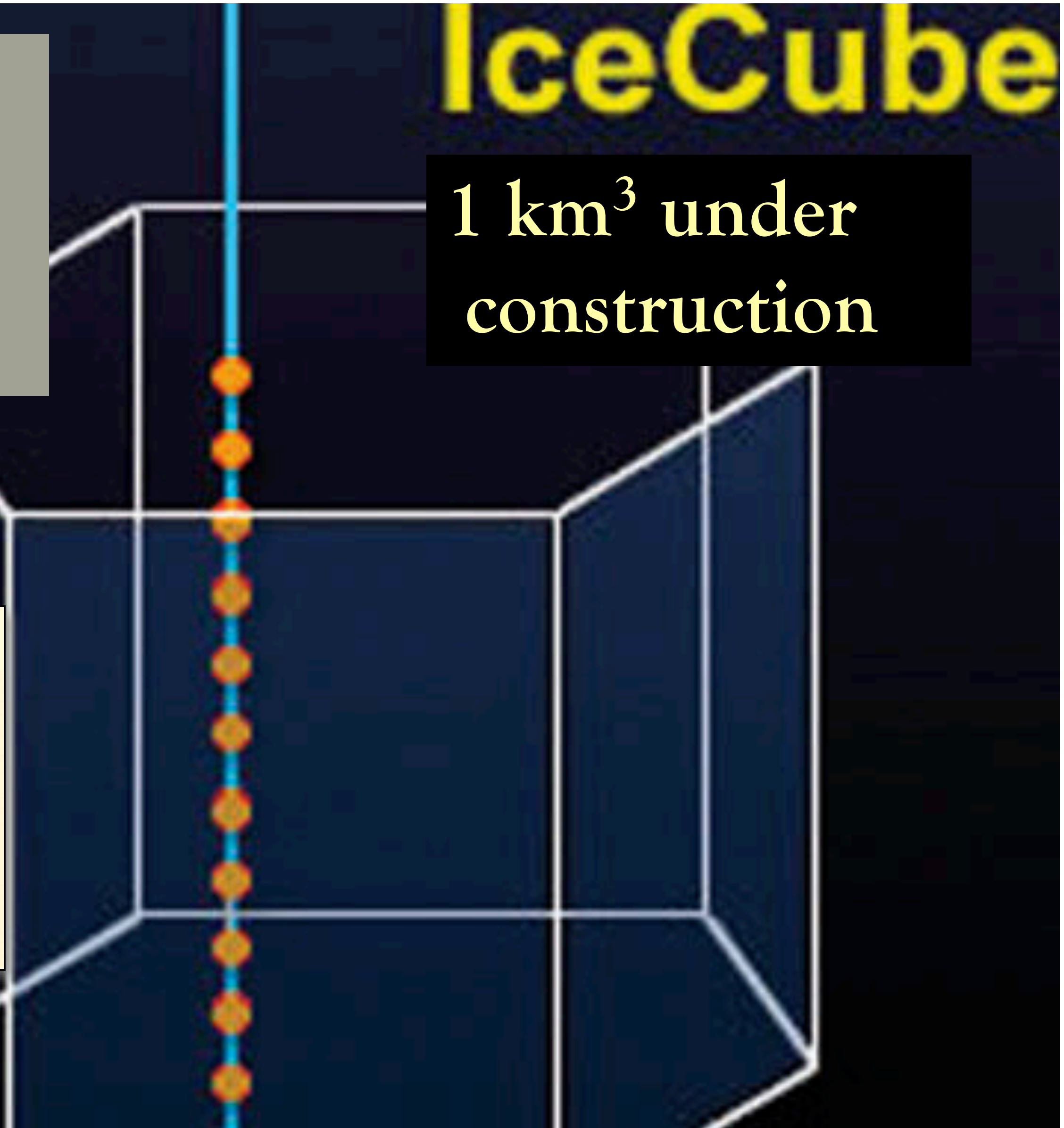
Nuclear Monitoring Requires Enormous Detectors

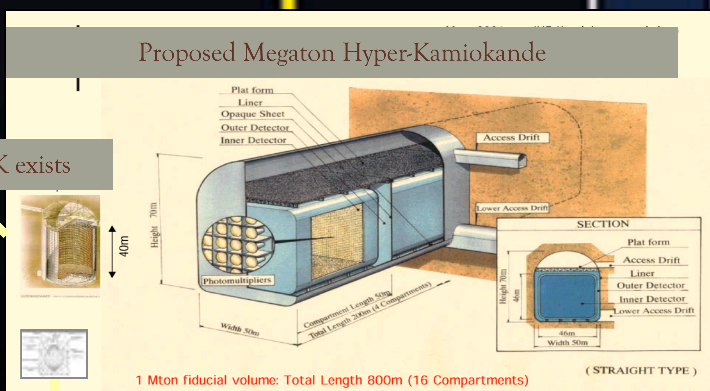
Single detector, *LE = Low Energy ~>MeV, HE = High Energy ~ >GeV*



Size for 25% measurement of reactor flux, 1 yr, no background.

1-10 Megaton Module Not Outlandish





1-10 Megaton units similar to sizes proposed for slightly higher energy, and much smaller than ICECUBE under construction.

Spinoff, Planetary Defense: Type II Supernova Early Warning

Silicon burning during last ~2 days prior to collapse detectable from whole galaxy!

Sudden increase in single neutron appearance

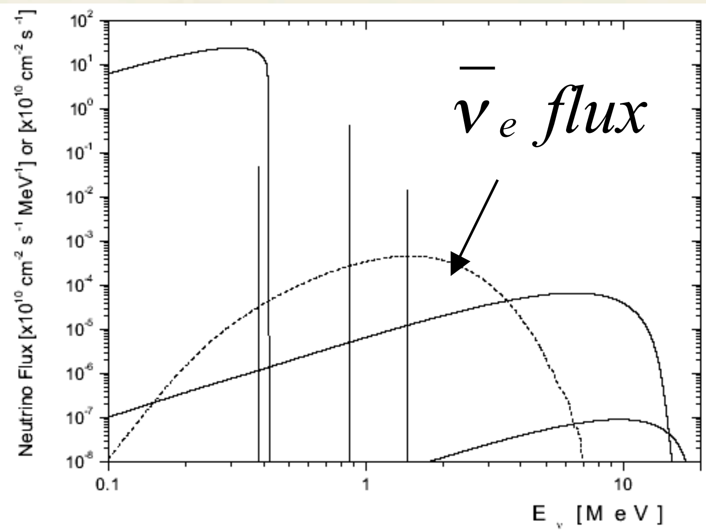


Fig. 2. The standard solar neutrino spectrum (BP2000, [5]) for pp fusion reactions in the Sun (solid lines) and the spectrum of pair-annihilation neutrinos emitted by a 20 $M_\odot$ star during silicon burning stage (dashed line). Star is located at a distance of 1 kpc.

Burning Phase	T_c [MeV]	ρ_c [g/cc]	μ_e [MeV]	L_ν [erg/s]	Duration τ	Total energy emitted [erg]
C	0.07	$2.7 \cdot 10^5$	0.0	$7.4 \cdot 10^{39}$	300 yrs	$7 \cdot 10^{49}$
Ne	0.146	$4.0 \cdot 10^6$	0.20	$1.2 \cdot 10^{43}$	140 days	$1.4 \cdot 10^{50}$
O	0.181	$6.0 \cdot 10^6$	0.24	$7.4 \cdot 10^{43}$	180 days	$1.2 \cdot 10^{51}$
Si	0.319	$4.9 \cdot 10^7$	0.84	$3.1 \cdot 10^{45}$	2 days	$5.4 \cdot 10^{50}$

Table 2
Properties of a 20 $M_\odot$ star according to Ref. [6]. We have calculated the total energy radiated in neutrinos as a product τL_ν. Actually, the neutrino emission is expected to be a function of time.

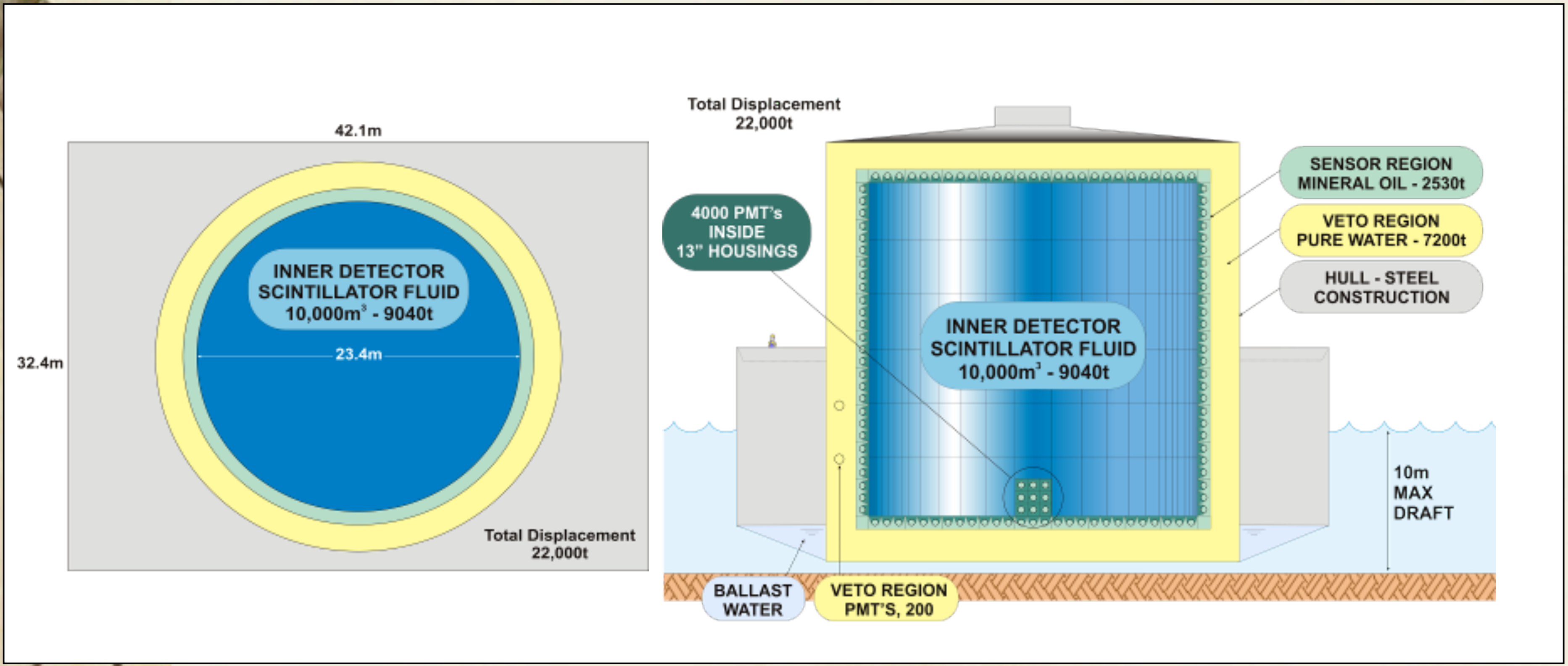
Odrzywolek, et al., astro-ph/0311012

Hanohano Science Outline

- **Introduction to project**
- **Neutrino Geophysics**
  - U/Th mantle flux
  - Th/U ratio
  - Geo-reactor search
- **Neutrino Oscillation Physics** *(new)*
  - Mixing angles θ_{12} and θ_{13}
  - Mass squared difference Δm^2_{31}
  - Mass hierarchy
- **Other Physics, Long range, Conclusions**

Hanohano - 10x "KamLAND" in Ocean

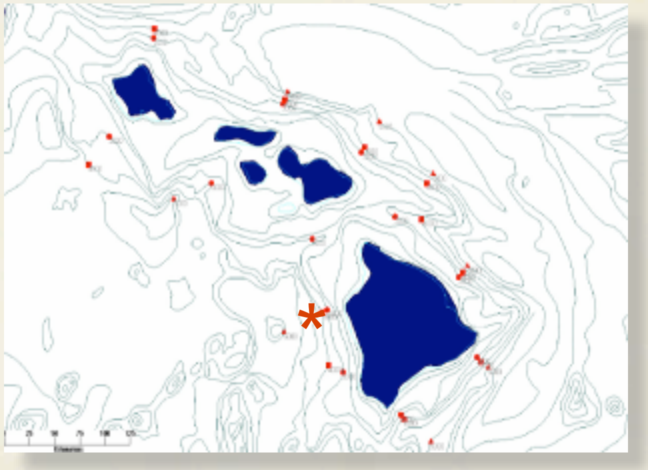
Construct in shipyard, fill/test in port, tow to site, and submerge to ~4 km



Hawaii Anti-Neutrino Observatory†

Location flexibility

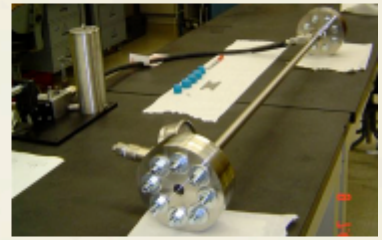
- Tow to various locations, cable connect
- Far from continental crust and reactors for neutrino geophysics- Hawaii, South Pacific, …
- Offshore of reactor for neutrino oscillation physics- California, Taiwan, …



Site survey done

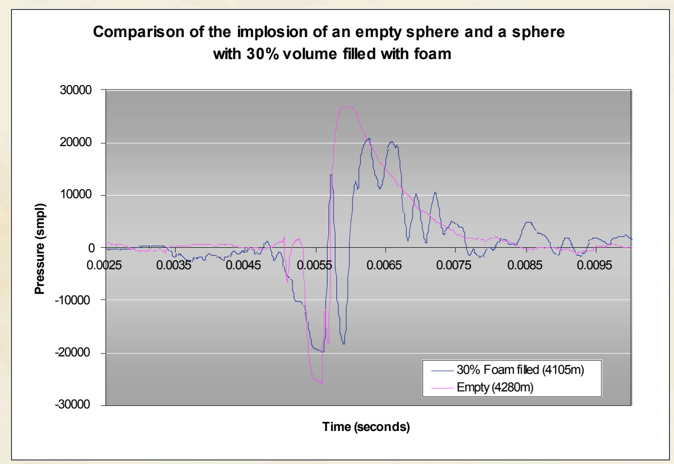
† *hanohano*- Hawaiian for distinguished

Technological issues being addressed



- Radiopurity technology exists
- Scintillating oil studies: P=450 atm., T=0^o
- Several choices available, safe, industrial

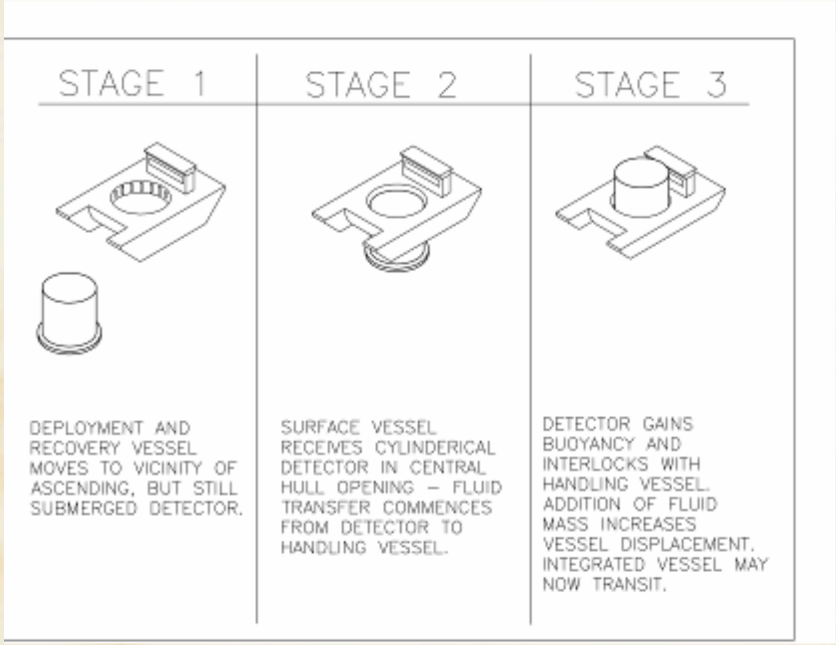
- Implosion studies at sea
- Engineering studies of detector structure, deployment



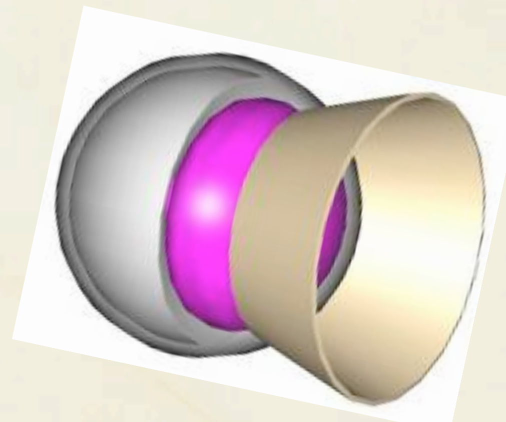
Actual Accomplishments: Structure

- Goal: workable vehicle at standard ship costs.
- Analyzed stability, weight, and structural strength vs scintillator volume, 5-120kT.
  - harbor, loading, testing, towing, submergence, landing, lift off, resurface, recovery.
- Single vehicle has problems with stability and weight, particularly larger sizes – Al is costly option.
- Shape is cylindrical, cube not constructable, 30m dia.
- Dual barge and detector module has much less weight and stability restrictions. Can build very large.
- 10kt Scintillator is nominal 22kT detector, lose ~0.9kT buoyancy on bottom. Ascent 46 min.
- Structure: $22m - OK

1/50 scale model test

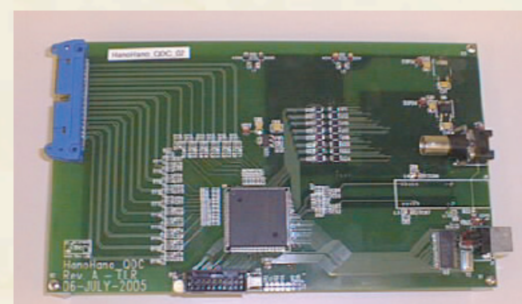


Actual Accomplishments: Photomultiplier Electronics



Completed electronics prototypes:

- PMT voltage supply manufacturers surveyed, sample devices in hand, several choices available (used in South Pole and Mediterranean experiments).
- PMT signal electronics prototypes constructed and tested at UH electronics facility, ready for second round for ocean tests.
- Signal digitization electronics prototypes constructed and tested at UH, ready for second round.
- No stoppers, power is as expected, need further refinement, reliability testing, etc. Adequate for proposal stage with predictable costing at this time.



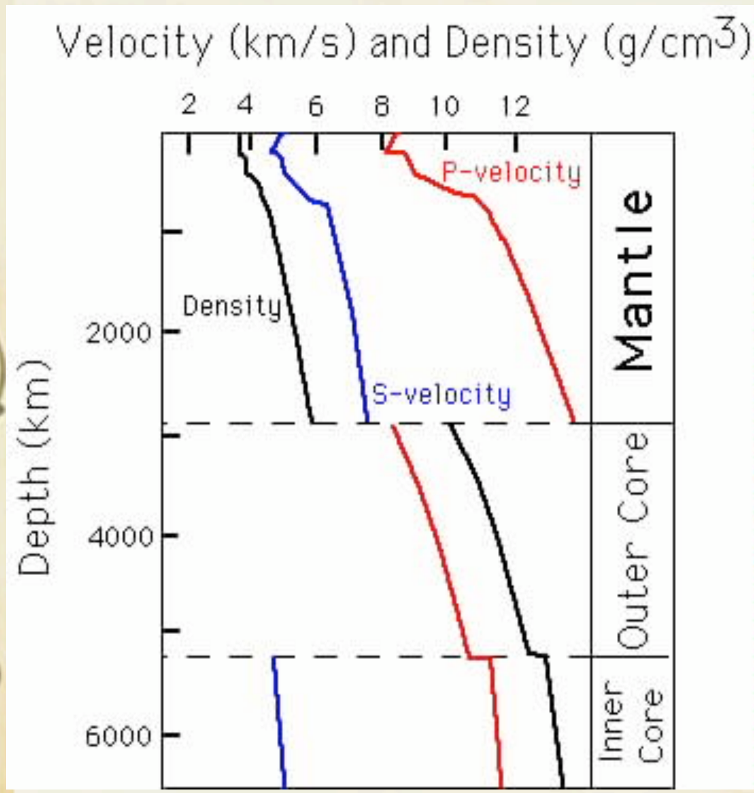
Geology: Big Questions

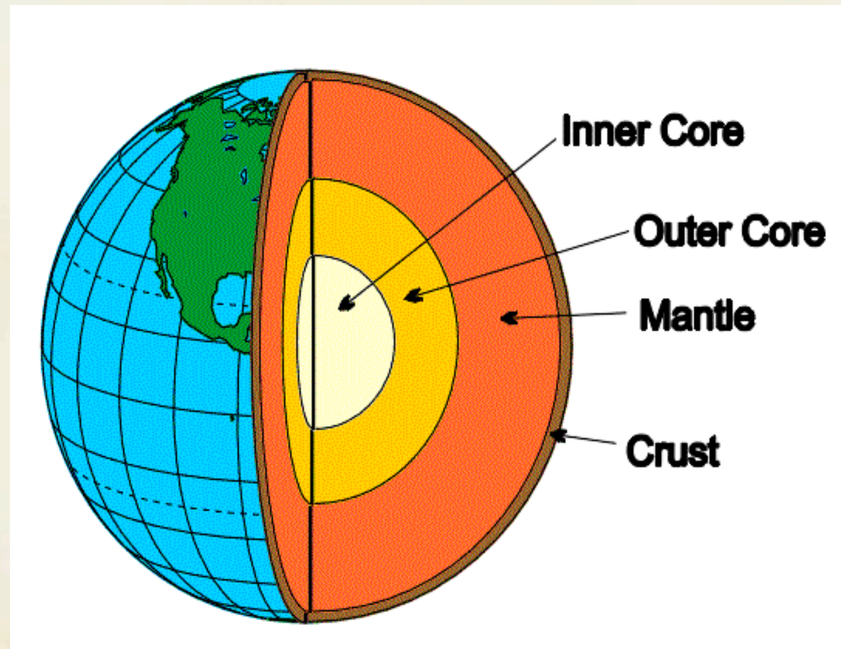
- What drives continental drift, mid-ocean seafloor spreading?
- What produces and sustains the geomagnetic field?
- How did the earth form?
- Of what is the deep earth composed?

▶ This experiment addresses all these.

Preliminary Reference Earth Model

Knowledge of Earth interior from seismology





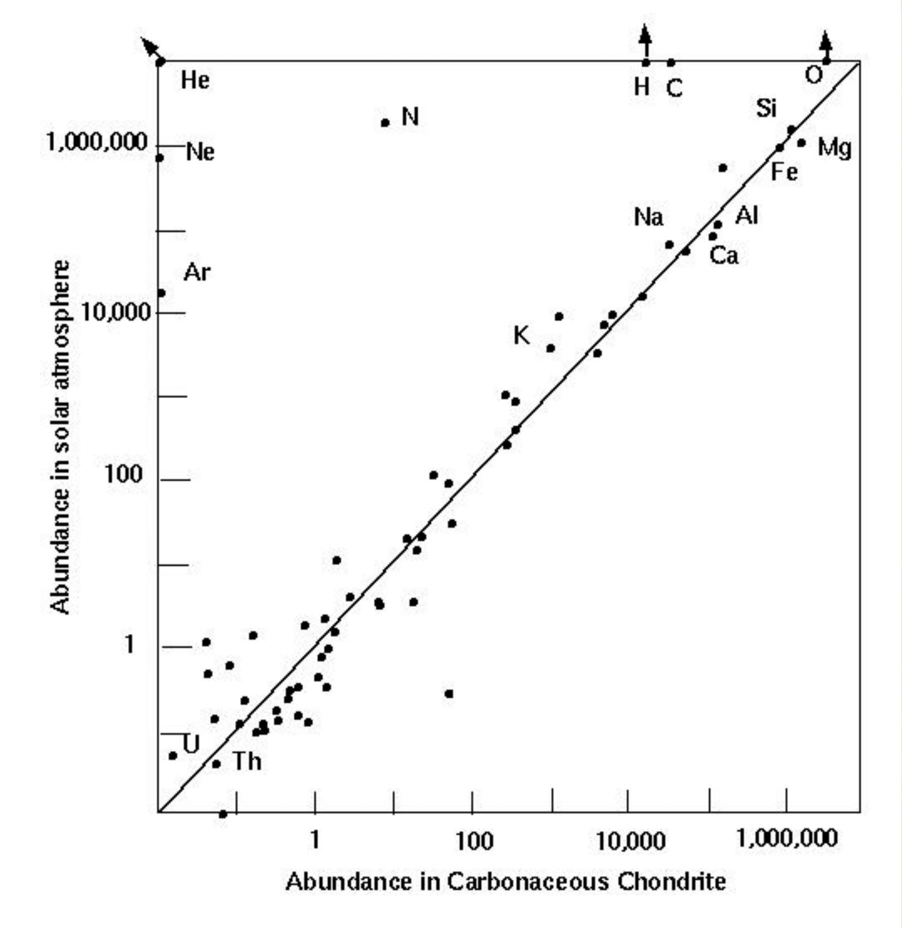
Dziewonski and Anderson, *Physics of the Earth and Planetary Interiors* **25** (1981) 297-356.

Measure velocity, use eq'n of state to infer density, guess composition.

Bulk Silicate Earth model

geologists "standard model"

Knowledge of Earth composition largely model dependent

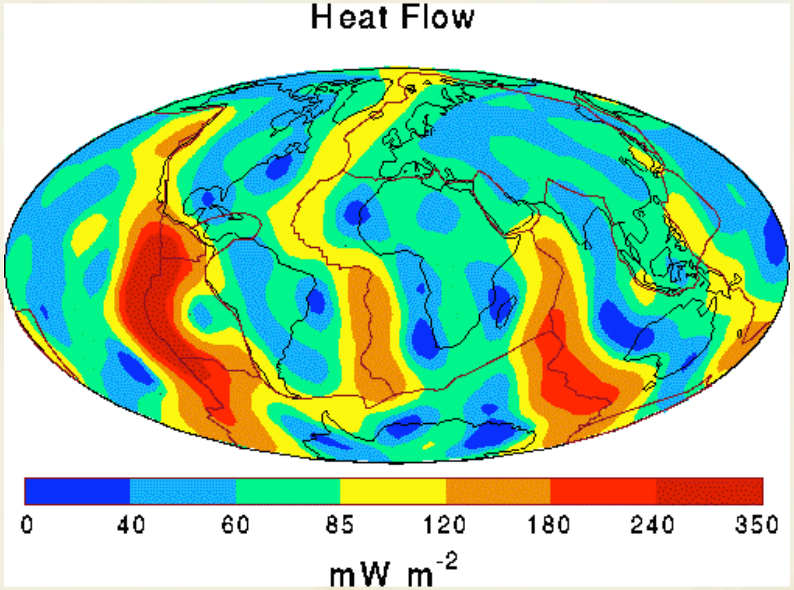


McDonough and Sun, *Chemical Geology* **120** (1995) 223-253.

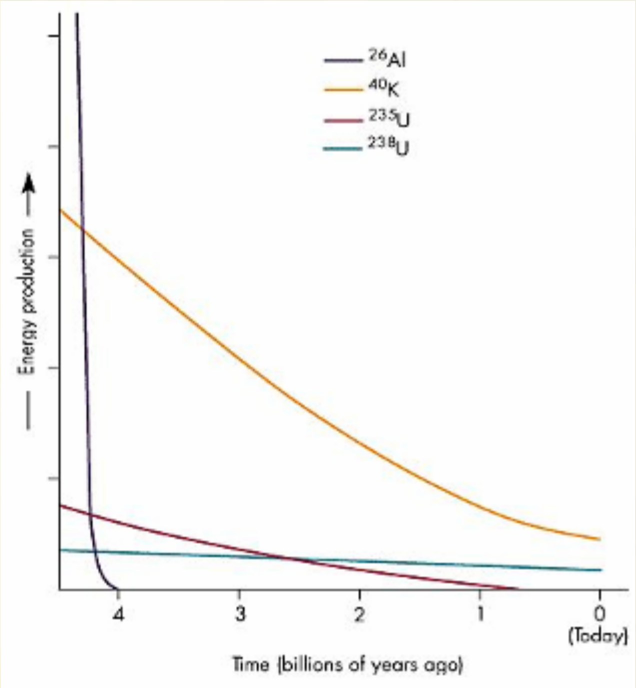
Mostly composition from three meteorites.

Terrestrial Heat Flow: 31-44 TW

Varies greatly, ocean spreading zones a problem



Time dependence a problem for geomagnetism

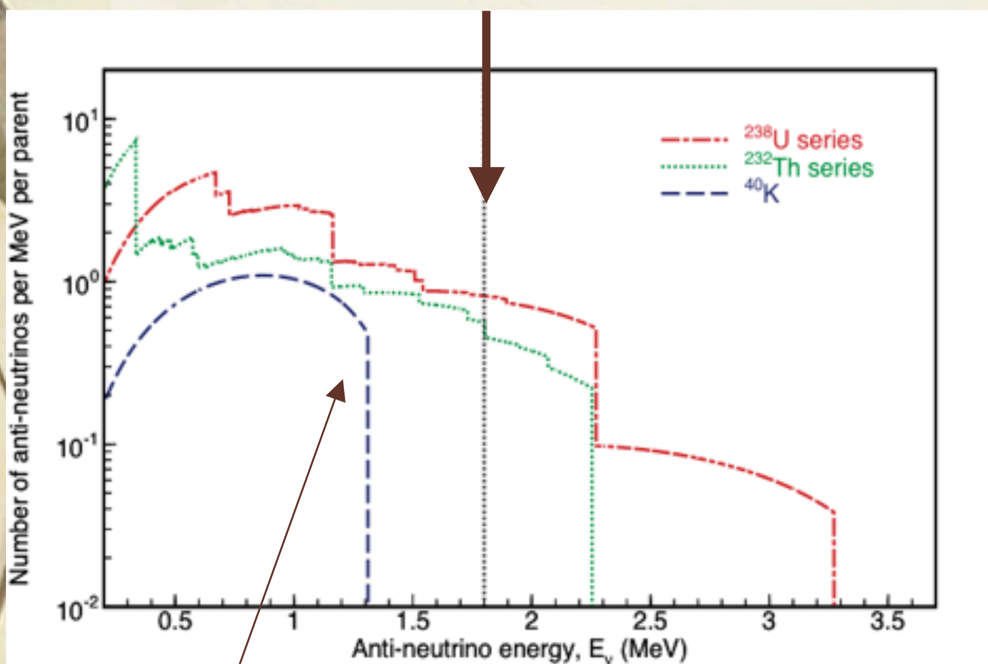


Pollack, Hurter, and Johnson, *Reviews of Geophysics* **31**(3) (1993) 267-280.

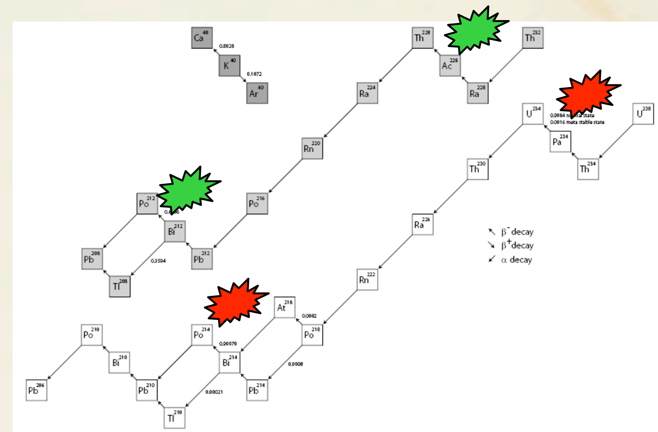
Hofmeister and Criss, *Tectonophysics* **395** (2005) 159-177.

Parent Spectrum Geo-Neutrinos

Threshold for Reines and Cowan coincidence technique

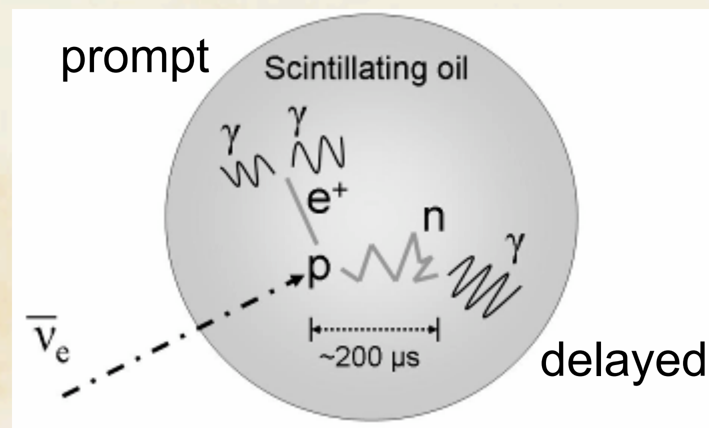


No present method for K nus.



thorium chain

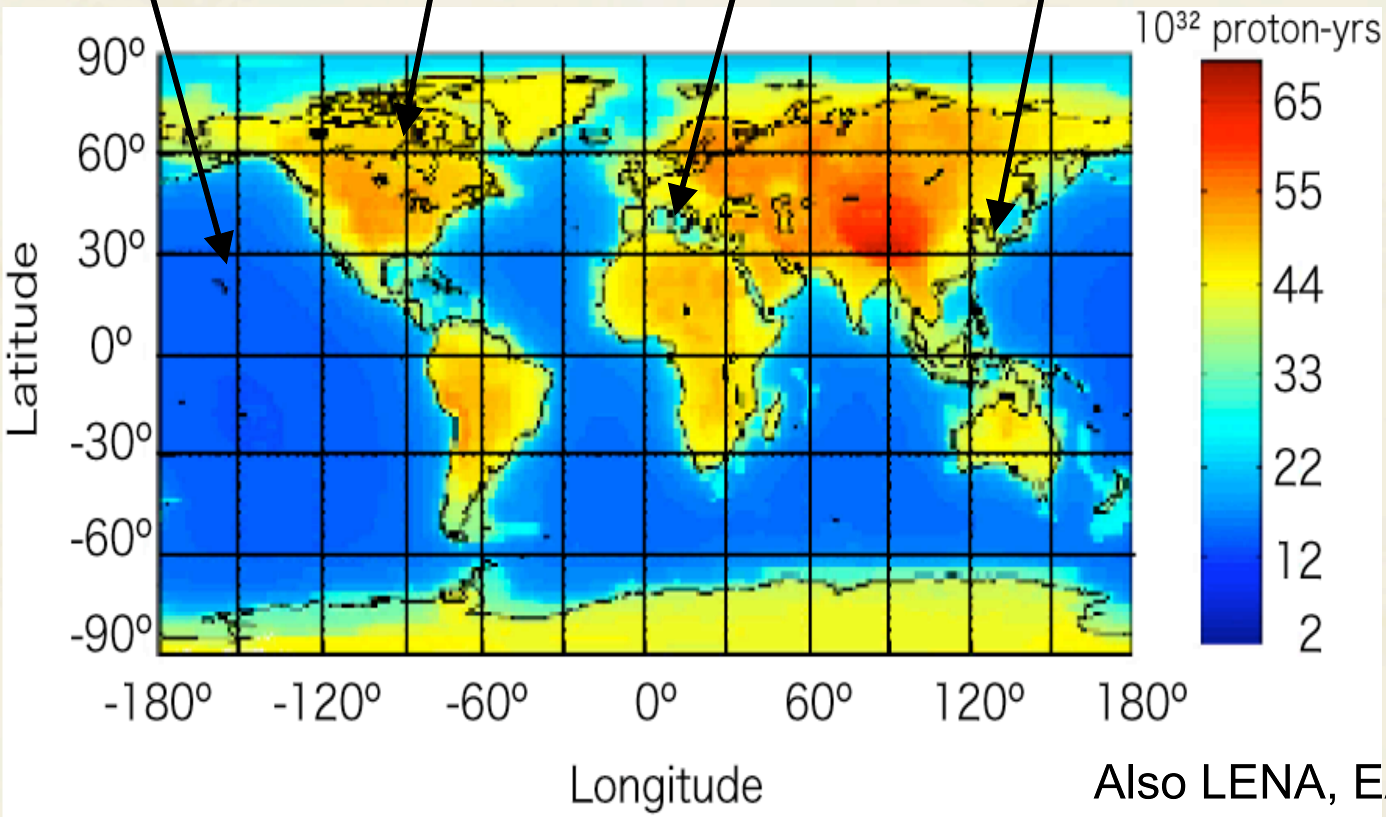
uranium chain



Predicted Geo-Neutrino Signal

Continental locations dominated by local crustal radioactivity.

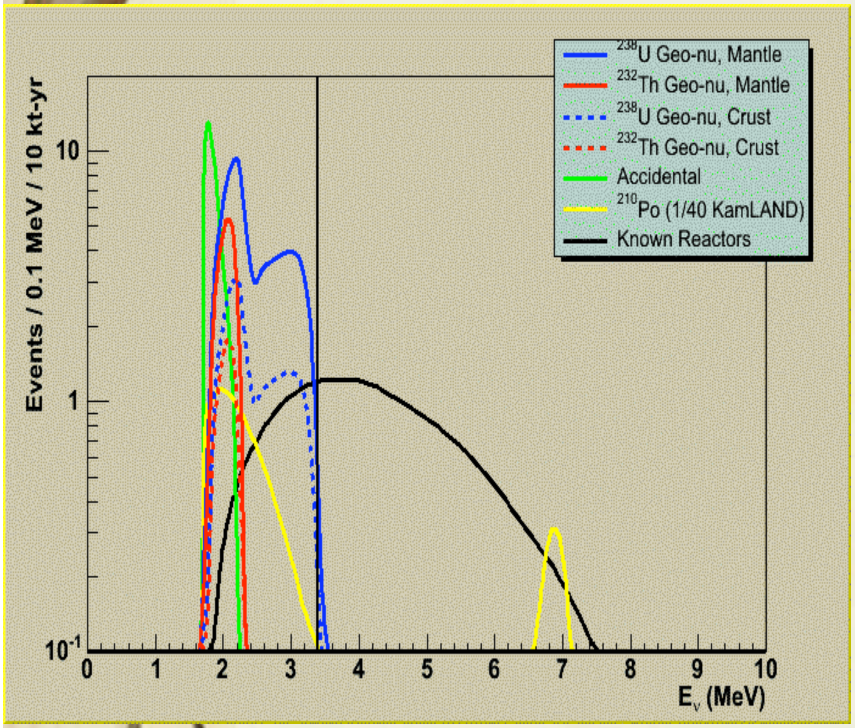
Hanohano **SNO+** **Borexino** **KamLAND**

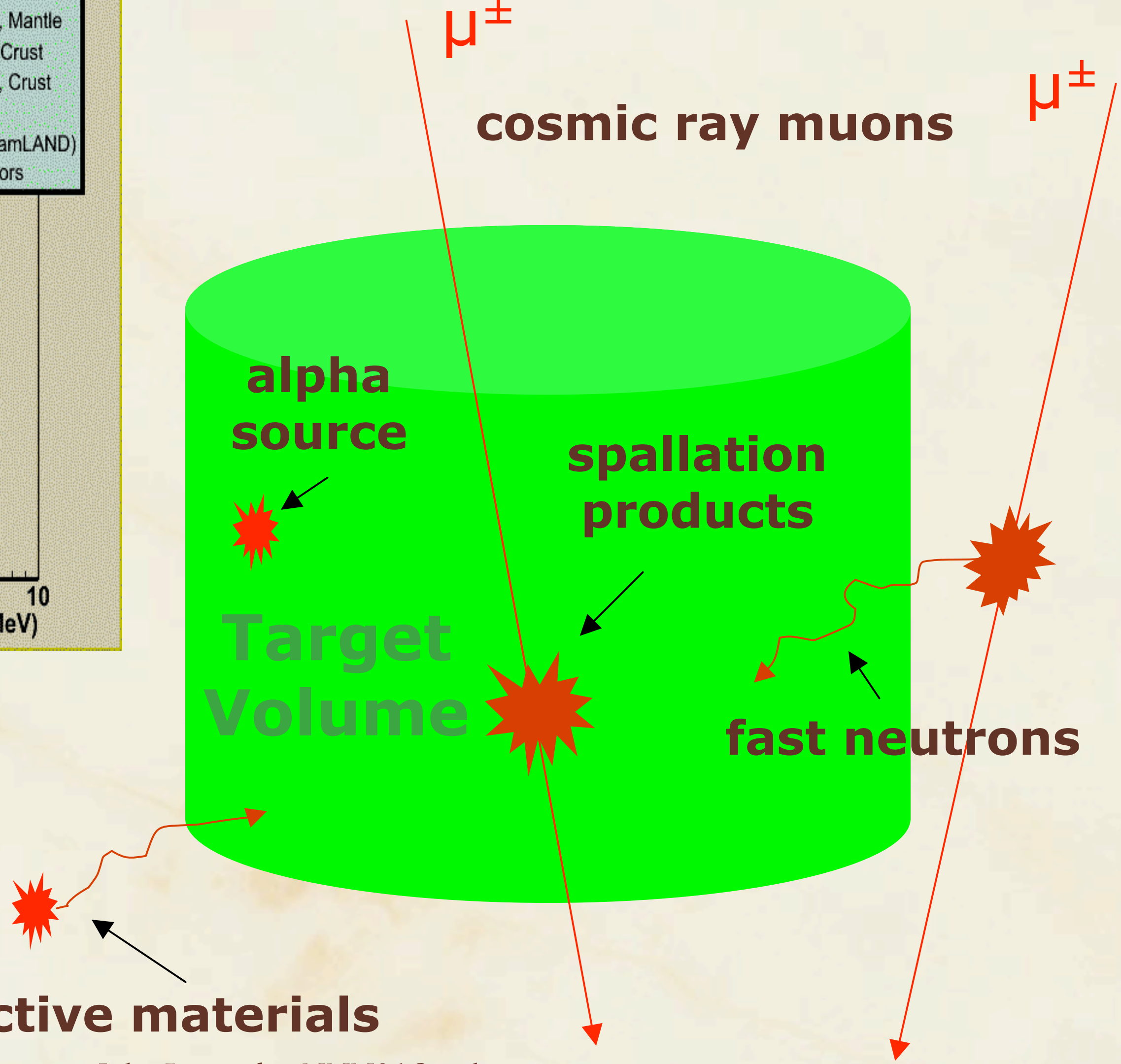


Also LENA, EARTH, Baksan… proposals

F. Mantovani *et al.*, Phys. Rev. D **69** (2004) 013001.

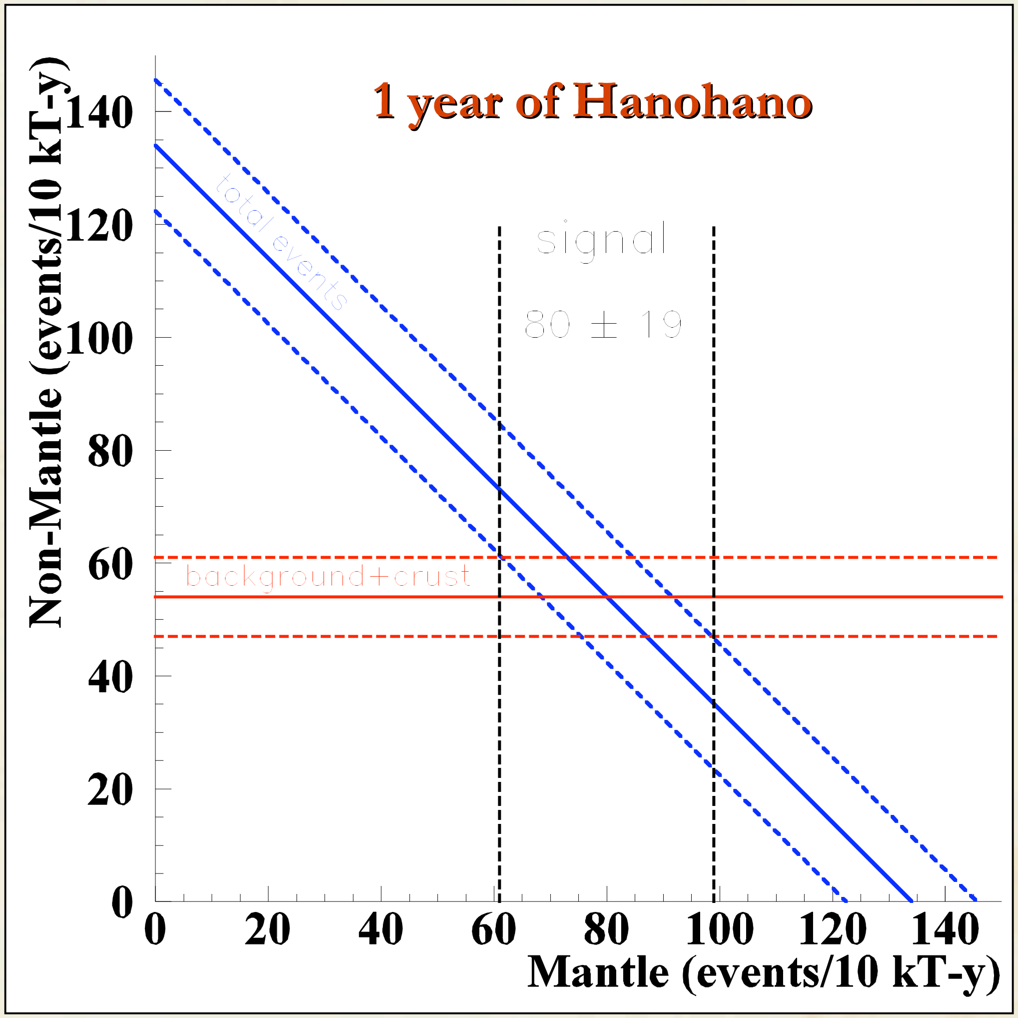
Geo-ν + Background Spectra

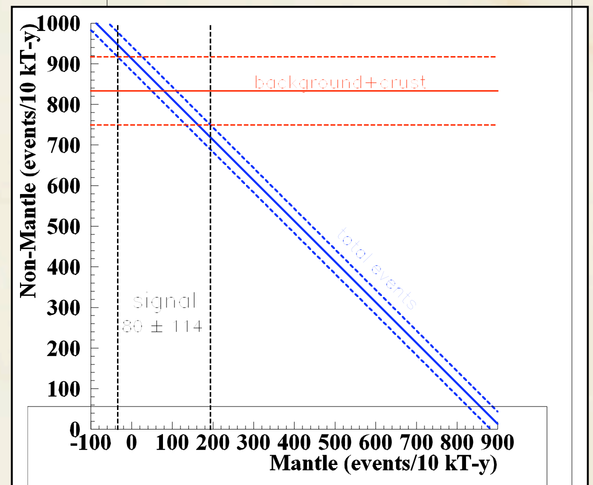




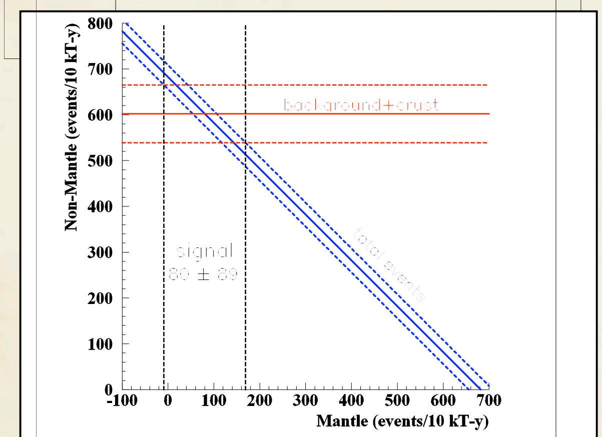
Hanohano: Mantle/Core Measurement

Must subtract uncertain crust flux to get that due to mantle/core.





15 years of SNO+



48 years of Borexino

Hanohano: Mantle Measurement

No continental detector can measure the mantle/core flux to better than 50% due to 20% uncertainty in crust flux

Earth Th/U Ratio Measurement

Project *crust type*	δR/R (1 yr exposure)	Th/U (1 yr exposure)	Years to 10% measurement
KamLAND *island arc*	2.0	4 ± 8	390
Borexino *continental*	1.1	4 ± 4	120
SNO+ *continental*	0.62	3.9 ± 2.4	39
Hanohano *oceanic*	0.20	3.9 ± 0.8	3.9

Statistical uncertainties only; includes reactors.

Geo-ν projects: Predicted Rates

Project *crust type*	Size (10^{32} free p)	Geoneutrino (events/y)	Crust (events/y)	Mantle (events/y)	Reactor (events/y)
KamLAND *island arc*	0.35	12.5	9.2	3.3	83.7
Borexino *continental*	0.18	7.6	5.9	1.7	6.2
SNO+ *continental*	0.57	30.0	24.7	5.3	35.1
Hanohano *oceanic*	8.7	112.2	31.3	80.9	12.2

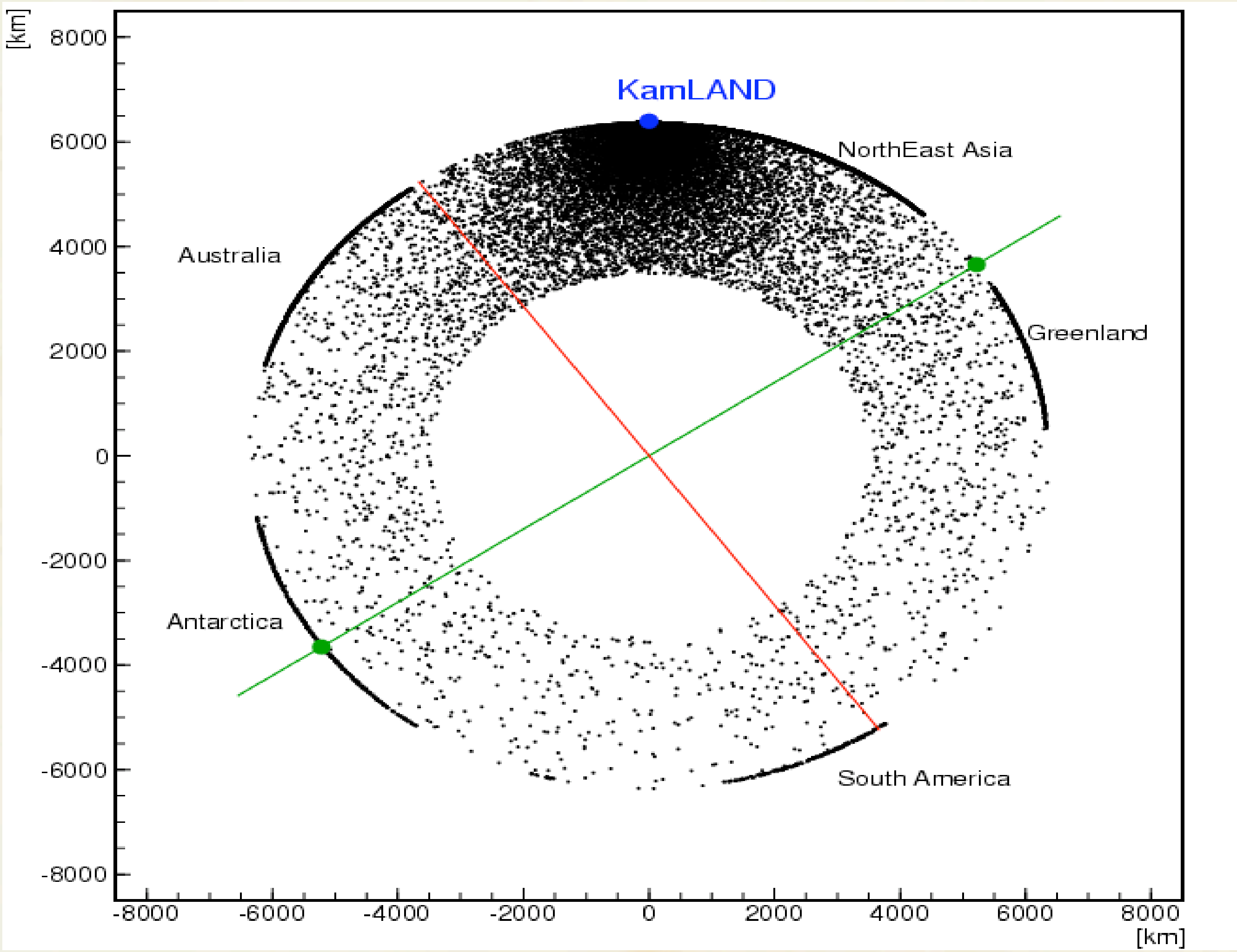
Measuring the Mantle

	Rate $(10\ kT\text{-}y)^{-1}$			
Source	**KamLAND**	**SNO+**	**Borexino**	**Hanohano**
Envir. Bkgd.	831 ± 196	18 ± 2	19 ± 2	12 ± 2
Reactor ν	1434 ± 129	438 ± 39	298 ± 27	12 ± 1
Crust ν	229 ± 46	377 ± 75	285 ± 57	30 ± 6
Non-Mantle	2494 ± 239	833 ± 83	602 ± 63	54 ± 7
Mantle	80 ± 16	80 ± 16	80 ± 16	80 ± 16
Total	2574 ± 240	913 ± 86	682 ± 65	134 ± 17
Signal	**80 ± 290**	**80 ± 117**	**80 ± 89**	**80 ± 19**

Note: while continental locations cannot measure mantle, combined measurements from all yield important geophysics.

Simulated Geo-Neutrino Source

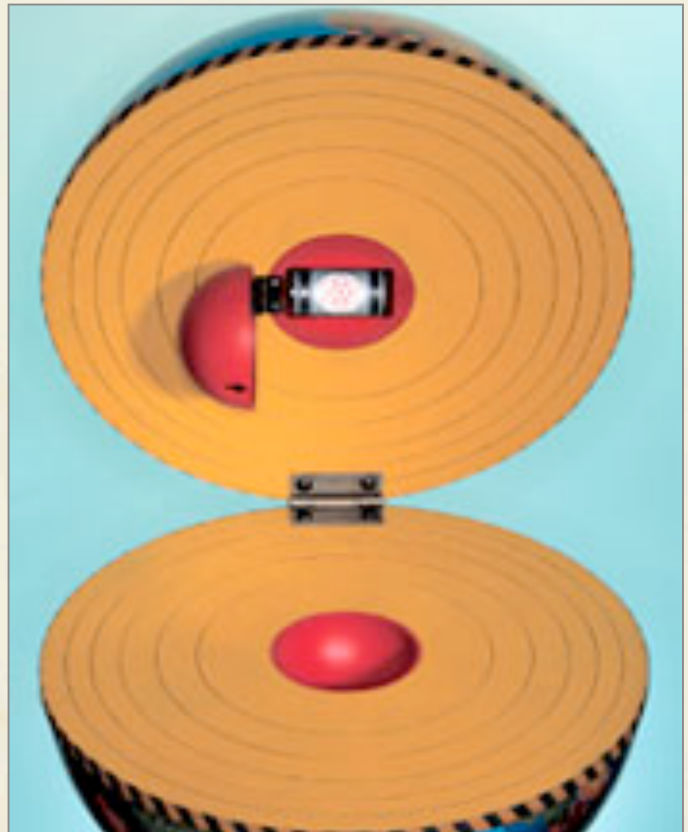
Weighted heavily towards local region of mantle.



Make observations at several sites to test mantle variation.

Anti-Neutrinos from the Core?

Herndon hypothesis: natural breeder reactor in core of Earth with P=1-10 TW

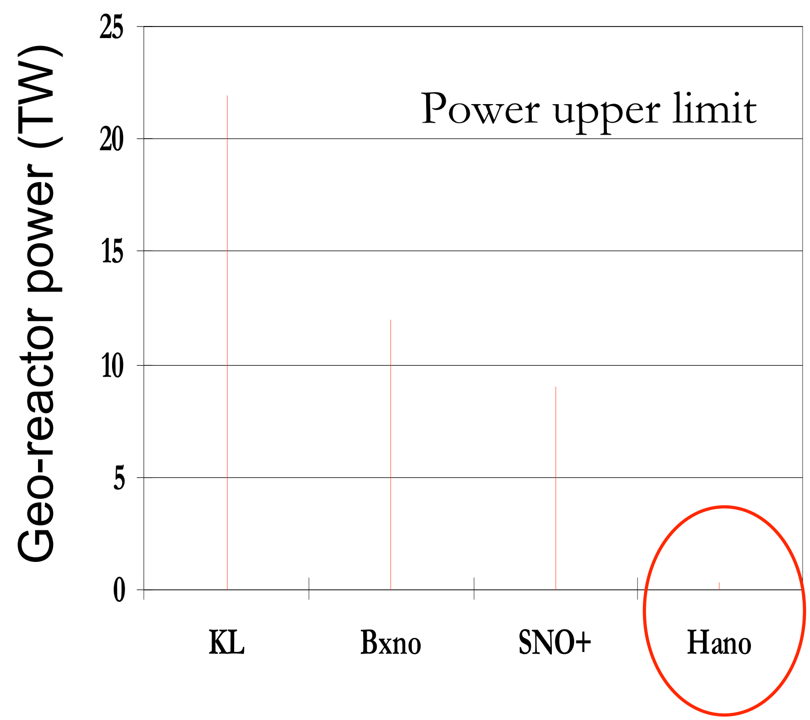


Geo-reactor hypothesis

Herndon, *Proc. Nat. Acad. Sci.* **93** (1996) 646.
Hollenbach and Herndon, *Proc. Nat. Acad. Sci.* **98** (2001) 11085.

Controversial but apparently not ruled out, and if true of tremendous importance.

Geo-Reactor Search



Project *crust type*	Power limit 99% CL (TW)	5σ discovery power (TW)
KamLAND *island arc*	22	51
Borexino *continental*	12	43
SNO+ *continental*	9	22
Hanohano *oceanic*	0.3	1.0

1 year run time- statistical uncertainties only

Need 1 – 10 TW to drive geomagnetic field.

Physics Big Questions: Neutrino Properties

- Non-zero neutrino mass and oscillations between flavors established.
- Filling in MNS-P mixing matrix needed.
- Need precise (few %) values.
- Quest for θ_{13}, need various approaches.
- Hierarchy of masses? ($m_1 < m_2 < m_3$?)
- CP violation? CPT?
- Importance to cosmology, grand unification….

▶ This experiment addresses many of these

3-ν Mixing: Reactor Neutrinos

$$
\left.
\begin{aligned}
P_{ee}=1-\{ &\cos^4(\theta_{13}) \sin^2(2\theta_{12}) [1-\cos(\Delta m^2_{21}L/2E)] \\
&+ \cos^2(\theta_{12}) \sin^2(2\theta_{13}) [1-\cos(\Delta m^2_{31}L/2E)] \\
&+ \sin^2(\theta_{12}) \sin^2(2\theta_{13}) [1-\cos(\Delta m^2_{32}L/2E)]\}/2
\end{aligned}
\right.
$$

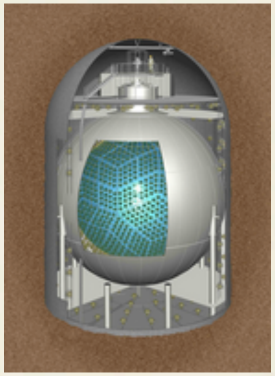
$\}$ wavelength close, 3%

→ Each of 3 amplitudes cycles (in L/E ~ "t")
with own periodicity (Δm^2 ~ "ω")

- amplitudes *13.5 : 2.5 : 1.0* above
- wavelengths ~110 km and ~4 km at reactor peak ~3.5 MeV

- ½-cycle measurements can yield
  - Mixing angles, mass-squared differences
- Multi-cycle measurements can yield
  - Mixing angles, precise mass-squared differences
  - Potential for mass hierarchy
  - Less sensitivity to systematics

Reactor & Atmospheric ν Mixing Parameters: Present Knowledge



- KamLAND combined analysis

  $\tan^2(\theta_{12})=0.40(+0.10/-0.07)$

  $\Delta m^2_{21}=(7.9\pm0.7)\times10^{-5}\ eV^2$

  Araki et al., *Phys. Rev. Lett.* **94** (2005) 081801.

- CHOOZ limit **$\sin^2(2\theta_{13}) \leq 0.20$**

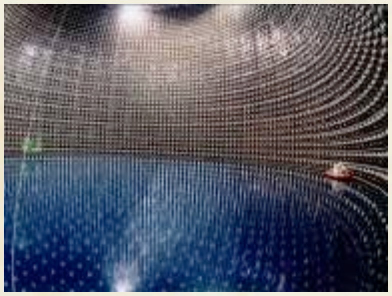
  Apollonio et al., *Eur. Phys. J.* **C27** (2003) 331-374.

- SuperK (and K2K)

  $\Delta m^2_{31}=(2.5\pm0.5)\times10^{-3}\ eV^2$

  Ashie et al., *Phys. Rev.* **D64** (2005) 112005

  Aliu et al., *Phys. Rev. Lett.* **94** (2005) 081802



Significant ν_e Flux Measurement Uncertainty Due to Oscillations

- Flux from distant, extended source like Earth or sun is fully mixed
- $P(\nu_e \rightarrow \nu_e) = 1 - 0.5\{\cos^4(\theta_{13})\sin^2(2\theta_{12}) + \sin^2(2\theta_{13})\}$

  $= 0.592\ (+0.035/-0.091)$

  Lower value for maximum angles

  Upper value for minimum angles
- $\Phi_{source} = \Phi_{detector} / P(\nu_e \rightarrow \nu_e)$

  Uncertainty is +15%/-6%

$\Rightarrow$ precise flux measures need θ_{12} & θ_{13}

Proposed ½-cycle θ_{13} Measurements

- Reactor experiment- ν_e point source
- Double Chooz, Daya Bay, Reno
- θ_{13} with "identical" detectors near (100m)/far(1-2 km)
- $P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2_{31} L/4E)$
- $\sin^2(2\theta_{13}) \leq 0.03$-$0.01$ in few years
- Solar angle & matter insensitive
- Systematics difficult

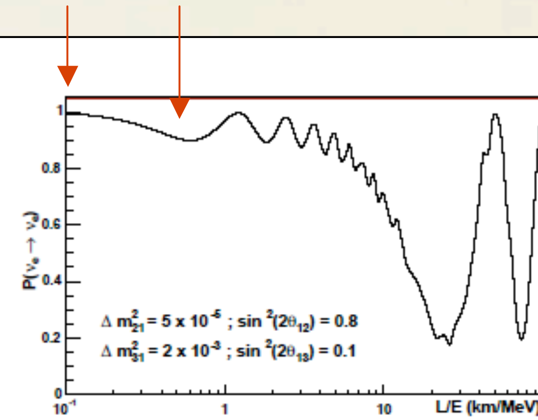


Figure 3: Probability of ν_e disappearance versus L/E for θ_{13} at its current upper limit

Figure 4: Schematic layout of a two detector reactor neutrino oscillation experiment.

Anderson, et al., hep-ex/0402041

Idea: L. Mikaelyan, V. Sinev, Phys. At. Nucl. 62 (1999) 2008, hep-ph/9811228.

Suggested ½-cycle θ_{12} Measurement

- Reactor experiment: ν_e point source at modest distance (10-100 km).
- $P(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2(2\theta_{12})\sin^2(\Delta m^2_{21} L/4E)$
- 60 GW ·kT ·y exposure at 50-70 km ->
  - ~4% systematic error from near detector
  - $\sin^2(\theta_{12})$ measured with ~2% uncertainty
- *We can do job without near monitor (?)*

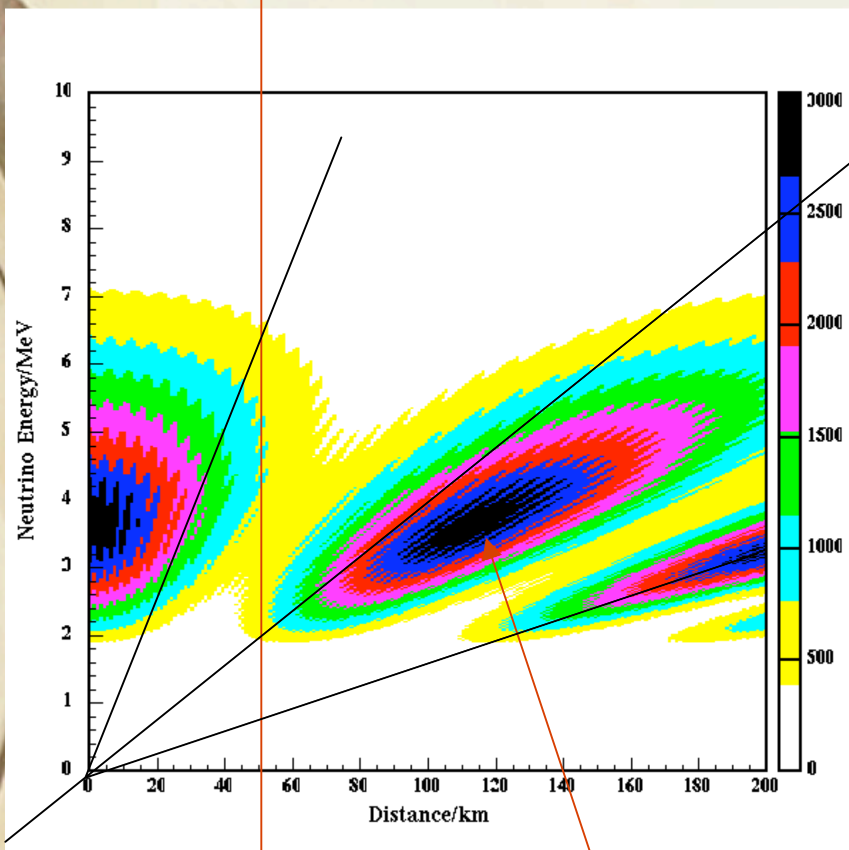
Bandyopadhyay et al., *Phys. Rev.* D**67** (2003) 113011.
Minakata et al., hep-ph/0407326
Bandyopadhyay et al., hep-ph/0410283

Energy Spectra, Distance and Oscillations

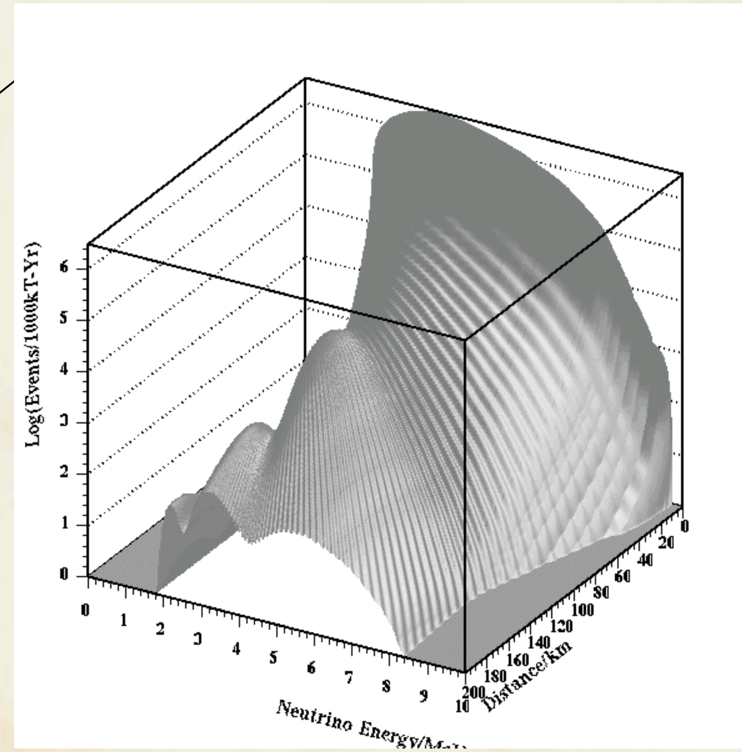
50 km study

Constant L/E

E



L

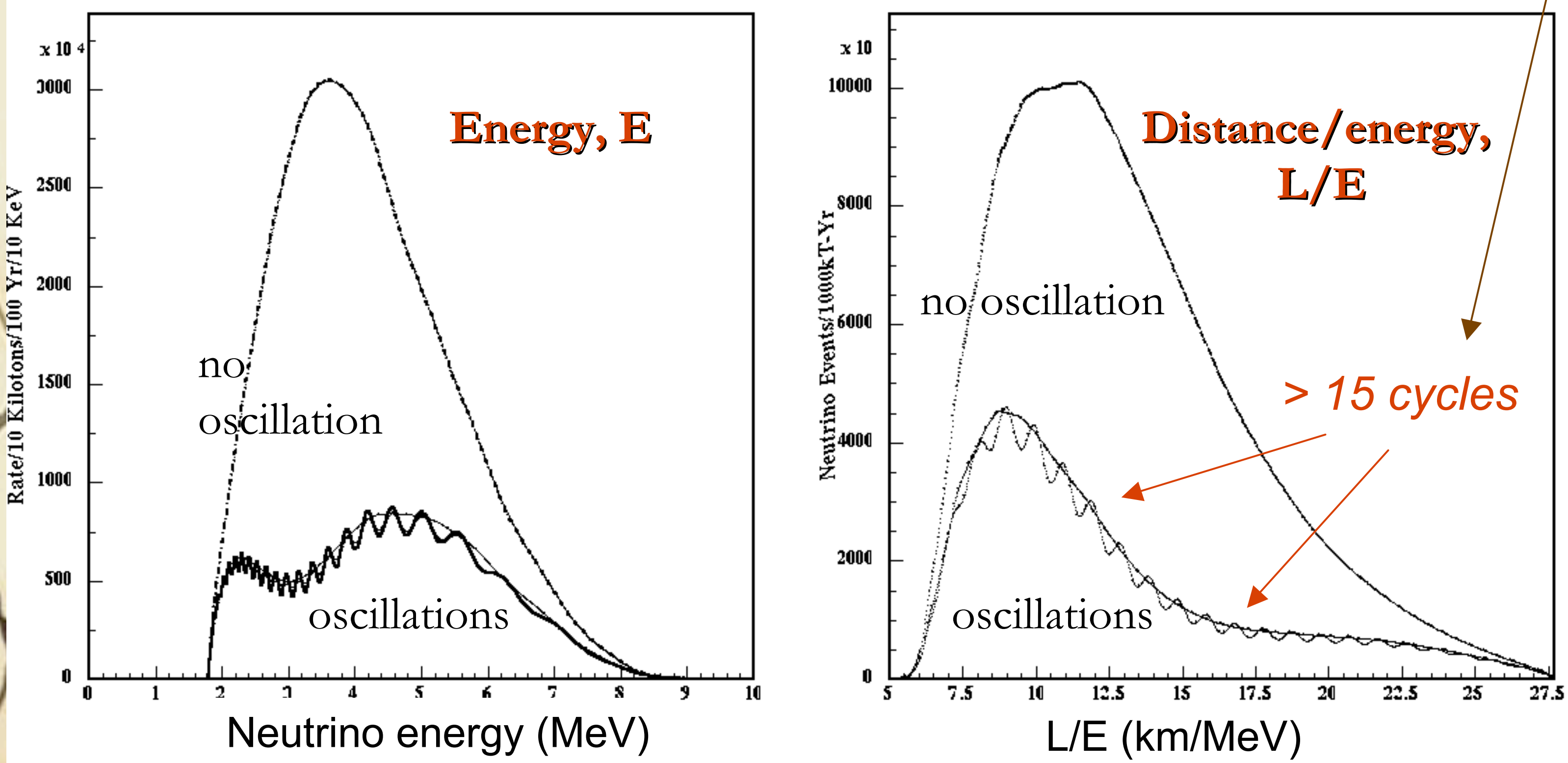


Log(Rate) vs Energy and DIstance

First return of
“solar” oscillation

Reactor Anti-Neutrino Spectra at 50 km

suggests using Fourier Transforms

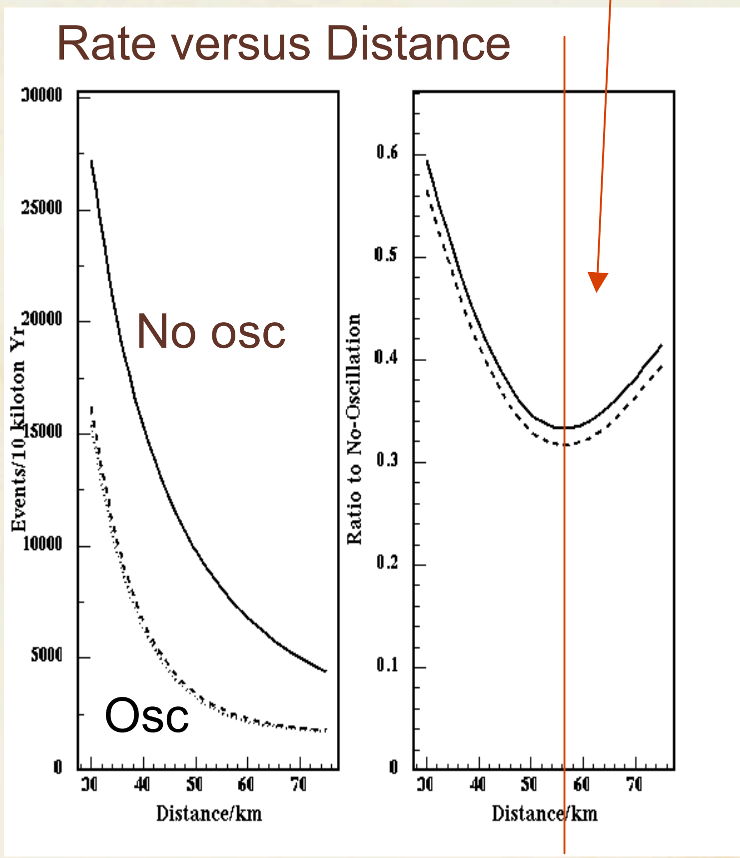


1,2 oscillations with $\sin^2(2\theta_{12})=0.82$ and $\Delta m^2_{21}=7.9\times10^{-5}$ eV^2

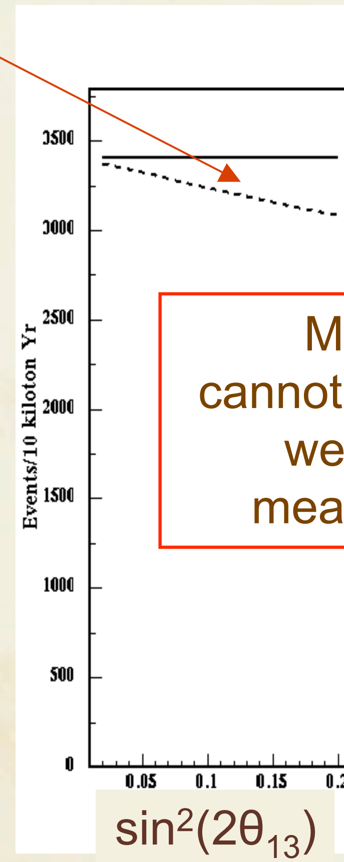
1,3 oscillations with $\sin^2(2\theta_{13})=0.10$ and $\Delta m^2_{31}=2.5\times10^{-3}$ eV^2

Rate versus Distance and θ_{13}

Note shift in total rate due to θ_{13}



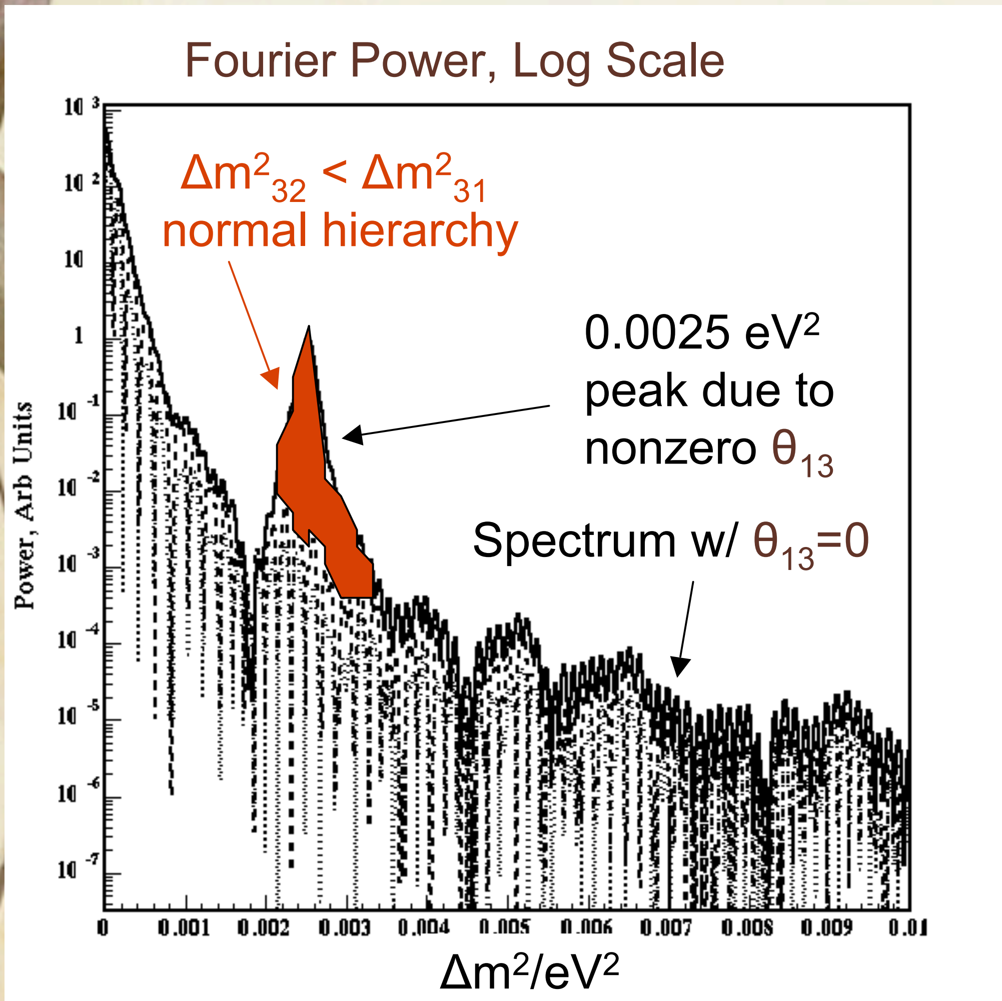
Rate Variation with θ_{13}



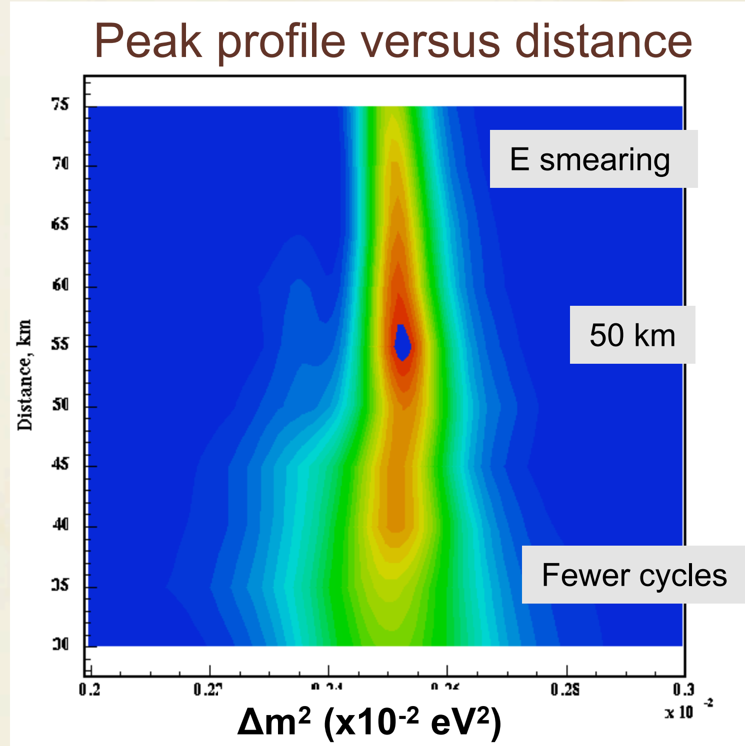
Message:
cannot measure θ_{12} well without measuring θ_{13}.

Max suppression
near 57 km

Fourier Transform on L/E to Δm^2



Includes energy smearing



Preliminary-

50 kt-y exposure at 50 km range

$\sin^2(2\theta_{13}) \geq 0.02$

Δm^2_{31}=0.0025 eV^2 to 1% level

Learned, Pakvasa, Svoboda, Dye *preprint in preparation*

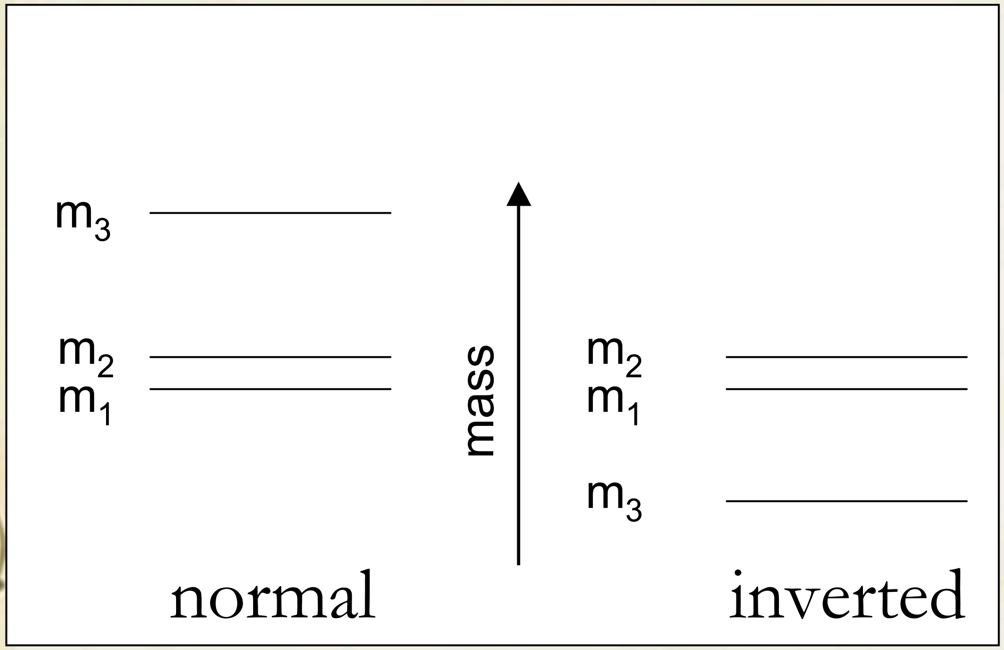
Beauty of Employing Fourier

(new realization, by us anyway)

- Normal statistical sqrt(n) Poisson errors apply to peak amplitude (mixing angle),
- but NOT to peak location… allows possibility for very precise measurement of Δm^2 (<1%?)
- Beats χ^2 and normal Max£, I think. (?)
- Employ signal processing tricks to maximize information extraction (ie. matched filter).

Neutrino Mass Hierarchy w/ Reactor Neutrinos ?

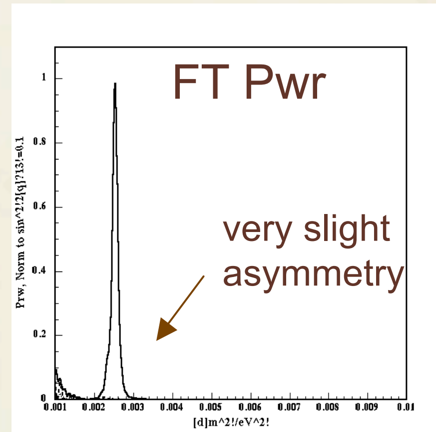
-needs work

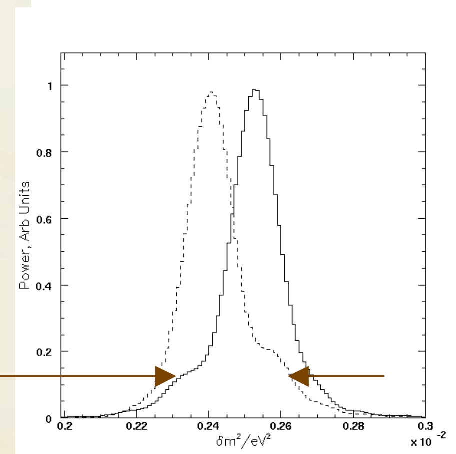


$|\Delta m^2_{31}| > |\Delta m^2_{32}|$ $|\Delta m^2_{31}| < |\Delta m^2_{32}|$

$$\boxed{\Delta m^2_{32} \approx (1 \pm 0.03)\Delta m^2_{31}}$$

Petcov and Piai, Phys. Lett. B533 (2001) 94-106.





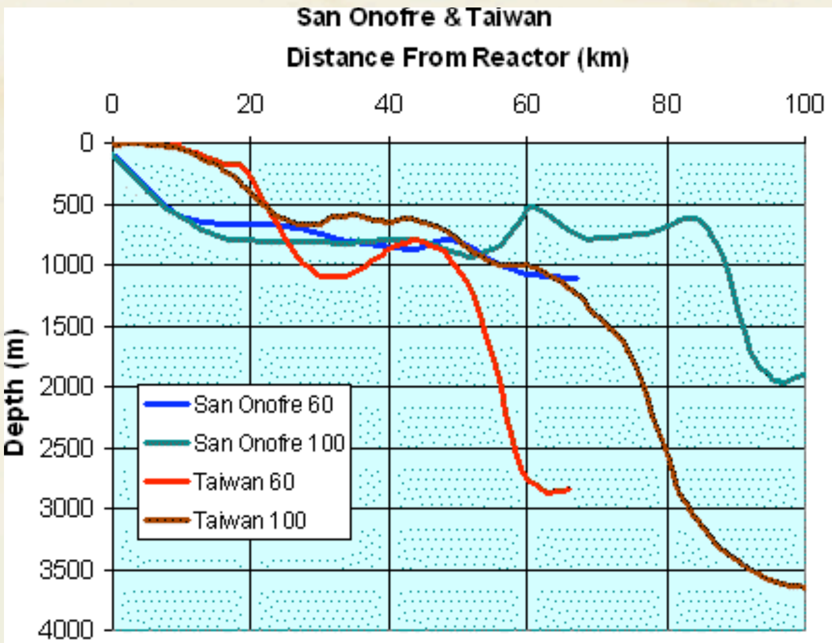
Peak has low-side small shoulder,

inv hierarchy shoulder on high-side.

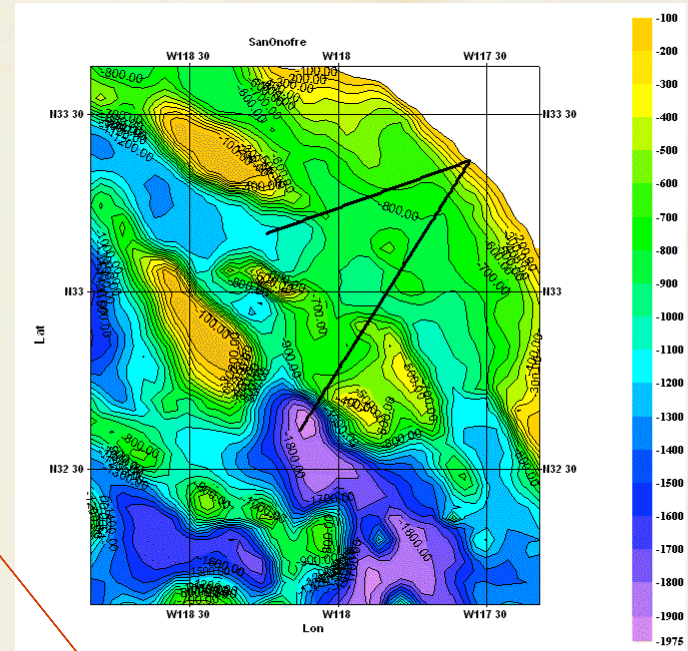
Normal and
inverted hierarchy

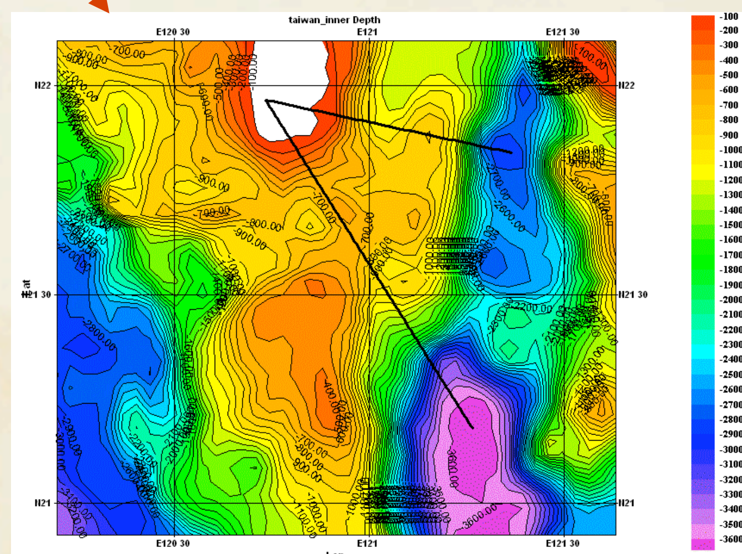
Hanohano - Candidate Reactor Sites

SW of San Onofre, **Calif**- ~6 GW$_{th}$
SE of Maanshan, **Taiwan**- ~5 GW$_{th}$



Depth profiles





Hanohano Science Summary

1 Yr, 10 Kiloton Exposures

- **Neutrino Geophysics, deep mid-ocean**
  - Mantle flux U/Th geo-neutrinos to ~25%
  - Measure Th/U ratio to ~20%
  - Rule out geo-reactor of P>0.3 TW
- **Neutrino Particle Physics, 50 km from reactor**
  - Measure $\sin^2(\theta_{12})$ to few % w/ standard ½-cycle
  - Measure $\sin^2(2\theta_{13})$ down to ~0.05 w/ multi-cycle
  - Δm^2_{31} at percent level w/ multi-cycle
  - No near detector; insensitive to background, systematics; complimentary to DC, DB, Minos, Nova
  - Potential for mass hierarchy with large exposure

Tests & Studies Needed

- Complete module anti-implosion work/tests.
- Demonstrate optical modules and scintillator in deep ocean.
- More scintillator studies, radiopurity, optimize choice.
- Further detector barge design and full costing.
- More detailed geological simulation, error analysis and study choice of deep ocean sites.
- Reactor distance and depth, including backgrounds.
- Can we do neutrino mass hierarchy with FT method?
- Neutrino direction studies.
- + Other physics: SN, relic SN, nucleon decay, … *(recall that this will be the largest low energy detector, 20x KamLAND, 10x SNO+, 50x Borexino, but 0.2x LENA?)*.

Conclusion

- First step in development of long range neutrino monitoring applications
- Hanohano
  - 10 kT deep ocean anti-neutrino observatory
  - Movable for multi-disciplinary science
    - Neutrino geophysics
    - Neutrino oscillation physics and more
  - Under development at Hawaii
  - 1st collaboration meeting 3/07 in Hawaii

interested? jgl@phys.hawaii.edu

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backups

Nucleon Decay with Hanohano

- PDK and SN data with geophysics studies…
- Nucleon Decay: kaon modes:
  - present: $\tau/b > 2.3 \times 10^{33}$ y *[Super-K, PR D **72**, 052007 (2005)].*
  - Hanohano: $\tau/b > 10^{34}$ y with 10 yr *[Lena PR D 72, 075014 (2005)]*
- Neutron Disappearance:
  - present: $\tau(n \rightarrow \text{invis}) > 5.8 \times 10^{29}$y at 90% CL

    $\tau(nn \rightarrow \text{invis}) > 1.4 \times 10^{30}$y at 90% CL

    [838 & 1119 metric ton-years of KamLAND, PRL 96 (2006) 101802]
  - Hanohano: $\tau(n \rightarrow \text{invis}) > 5 \times 10^{31}$ y at 90% CL 10 yrs

    $\tau(nn \rightarrow \text{invis}) > 5 \times 10^{31}$ y at 90% CL

Simulations needed